Transactions, **SMiRT-26**
Berlin/Potsdam, Germany, July 10-15, 2022
Division 05

Soil-structure-interaction sensitivity to earthquake level. Case of a deeply embedded nuclear building in soft soil

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ABSTRACT

This paper focuses on the example of a deeply embedded structure built at Krško nuclear power plant within safety upgrade program. This Ultimate Safety Building is designed against extreme external hazards, in particular for very high PGA. Seismic analyses and floor response spectra are computed with the help of SASSI software by direct solution method. Soil compatible properties are previously determined by site response analyses using SHAKE software for different earthquake levels, making the effective dynamic soil properties decreasing actually from soft to very soft. Final results of the study exhibit non-linear sensitivity of the building response to PGA intensity, interpreted as a natural moderator effect coming from particular local soft soil conditions. It is remarkable that acceleration response of the building is mostly driven by soil-structure-interaction effects, under the simple form of rigid body translation modes, but the response does not increase proportionally to the PGA intensity, because of modal frequency sensitivity and damping variations. Secondary modes effects vary in frequency, damping, but also in deformed shape, thus making some floor response spectra secondary peaks disappear when the seismic level rises. Comparison with simplified impedance model is presented to estimate the composite damping ratio and to illustrate how the direct solution method can enable to reduce over-conservatism in very high seismic conditions. Sensitivity to diaphragm wall construction pit modeling and nearby buildings is also investigated.

INTRODUCTION

Incorporating soil-structure-interaction (SSI) effects in design of nuclear civil buildings has become common practice for years. As various methodologies and tools exist over the engineering community and regulations, with different levels of complexity and accuracy, it is remarkable that IAEA has lead an expert working group to establish state of the art TecDoc (2017) in the framework of International Seismic Safety Centre missions.

In general, SSI influences the system response in three ways (see Crouse 2000)

- It alters the dynamic characteristics of the soil-structure system, such as modal frequencies and vibrating mode shapes (inertial interaction effects). In particular, the fundamental period is lengthened, and rigid body motion modes of the structure appear. These modes become predominant when the soil is softer.
- It increases the modal damping as part of the soil contributes to the overall damping of the soil-structure system (material damping + radiative damping).
- It modifies the wave propagation in the ground and the free-field ground motion (kinematic interaction effects)

Basically, in most situations, the degree of influence of SSI on response of structure can be roughly evaluated by simple usual formulations. The horizontal flexible-base period and damping ratio depend on the soil and building characteristics, the nature of motion and its frequency. They can be evaluated in first estimate from:

$$\frac{\tilde{T}}{T} = \sqrt{1 + \frac{k}{k_u} + \frac{k.h^2}{k_\theta}} \qquad (1) \qquad\qquad \tilde{\xi} = \xi_f + \frac{\xi}{(\tilde{T}/T)^3} \qquad (2)$$

where T, k and h are the period, the stiffness and the effective modal height of the fixed-base build-ing (approximately two third of the overall structure height for building with regular geometry and uniform mass distribution) ; ku and kθ are the soil impedances in translation and rocking ; ξf and ξ are the foundation soil damping ratio and building damping ratio (4% to 7% depending on applicable codes and seismic level for concrete structure) respectively.

Thus, in soft soil conditions (relative to the building stiffness), the resulting flexible-base composite damping ratio and the period of vibrations are mainly driven by the foundation characteristics. Figure 1 illustrates SSI effects on acceleration when period T and damping ratio ξ are modified. Note that reality is actually more complex because SSI damping is frequency dependent. Finally, seismic demand can be increased or decreased, depending on the position on the design spectrum (ascending or descending branch) and the considered level of damping.

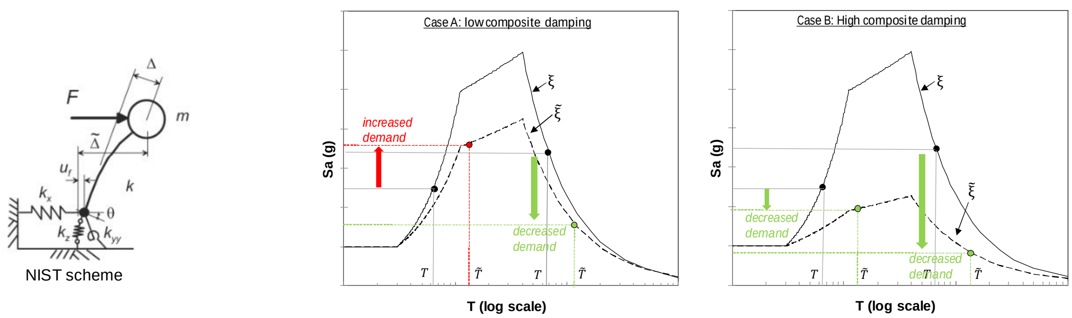


Figure 1. Inertial SSI effects on spectral acceleration associated with period lengthening and damping increase

Foundation soil damping ξ_f consists of:

- the material damping generally 5% minimum for soft-medium soil, reaches higher value when site response analysis of a soil column is carried out in first step, to account for the fractional loss of energy per cycle in the waves instead of being totally transferred through medium. Regulations generally specifies that in no case should the material soil damping as expressed by the hysteretic damping ratio exceed 15% (see NUREG 2007)
- the radiation damping associated with the generation, propagation and reflection phenomena of seismic waves into the soil medium by the motion of the foundation system relative to the free field earthquake motion.

So, the hysteretic damping primarily depends nonlinearly on strain induced in the soil during the shaking, whereas the radiation damping depends on the elastic properties of the surrounding soil, the shape and embedment of the foundation, and the surrounding structures in the ground.

One usual engineering practice, even for embedded building, is that when derived by impedance functions, the soil-structure interaction (SSI) is represented by systems of impedance matrix or alternatively by systems of springs located at each node of the interface, so as to reproduce adequately the global behaviour of the soil, the foundations and the building together. Springs characteristics are set at the relevant main modal frequencies in each translations and rotations. Most simplified approach to assess the soil impedance in terms of frequency dependent stiffness and damping is to refer to analytic formulations for surface or embedded foundations (ex: Gazetas 1991). However, their validity domain is generally limited to simple foundation geometries, homogeneous soil and a small range of frequencies. In other situations, the use of specific softwares appears necessary to deter-mine impedance functions.

Drawbacks of such impedance model method (called “halfspace or substructure solution technique” in NUREG wording), even when the impedance function is computed accurately, are basically that:

- impedance matrix characteristics are set at only one frequency per global degree of freedom after iterative calibration modal analysis procedure based on the fundamental modes in each direction, so that they cannot reflect exactly the higher modes frequency dependent SSI impedances. Such method sounds therefore only acceptable for simple response dominated by one mode (ex: regular shape building ; rigid body SSI response).
- composite modal damping is often limited by design codes for use in modal/spectral analyses or time domain analyses (ex: 20% in NUREG SRP 3.7.2 and ASCE 4-98, 30% in ASN guidelines, 30% in RCC-CW, 15%-30% in ETC-C or ISDCB codes). Consequently, as radiation damping could be actually very high in some cases, impedance method results may be overly conservative. Figure 1 even illustrates that seismic forces could be wrongly increased instead of being decreased when underestimated damping is considered (see ascending branch case A and B). Yet, Ostadan (2004) stated that whatever the method (time domain or frequency domain), one could obtain actually similar and reasonable results if consistent assumptions are made and the different model parameters are wisely selected, especially damping. But, correct calibration of composite damping is not easy task, especially when the system cannot be represented by only one mode per degree of freedom.

Many examples can be found in the literary about SSI damping values. However, information is al-ways focused on translation damping ratio, whereas rotational modes can play significant role and generate secondary peaks on floor response spectra. Moreover, examples correspond to soil conditions from soft to rock, but rarely very soft.

Case study of an Ultimate Safety Building is presented in this paper. The structure is deeply embed-ded into soft soil and designed in accordance with American rules. Regulations for the seismic design of nuclear power plants permit direct soil-structure interaction analyses in frequency domain, with the full effects of radiation damping without any limitations. So, for that project, as the design seismic level is already very high, and in order to guarantee feasibility of the components inside, it was decided to compute optimized floor response spectra by the “direct solution technique” (as NUREG wording). The building, foundations, and the soil are modeled using finite element method (FEM) and analyzed in single step. Time-history computations are performed in frequency domain then by an inverse FFT to come back in time-domain. Calculations are run for 3 seismic intensities, considering as input the respective compatible dynamic soil properties.

KRSKO NPP SAFETY UPGRADE PROGRAM

Nuklearna Elektrarna Krško (NEK) has been implementing, in the frame of the plant's long-term operations activities, a Safety Upgrade Program to address the safety implications highlighted by the Fukushima event, and to take measures towards implementing passive safety engineering features, which has recently being used in the +III generation of nuclear reactors. The three-phased program represents one of the most complete and consistent responses of the nuclear industry to the Fukushima event. Within that Program, bunkered building 2 (BB2) is constructed inside Krsko’s yards. Main functions are to host pumps and tanks, and all associated support functions, for the Alternate Safety Injection (ASI) and Alternate Auxiliary Feedwater (AAF) systems, in order to lessen the chance of a severe accident and to improve the means to successfully mitigate the consequences, should it occur despite defense in depth principles.

Industrial scheme of the project is as follows: NEK is Owner ; Ansaldo Nucleare acts as Main Con-tractor of Engineering, Procurement and Construction, with the support of various local companies. As a subcontractor, Tractebel is in charge of structural design, and introduced also Dynamis Associates in the project as SASSI experts. Moreover, independent peer review was ordered to an Authorized Institution (University Ljubljana, Faculty of civil and geodetic engineering) delivering technical approval within the licensing procedure from Slovenian nuclear authorities.

BB2 is seismic category I building, located ~150m far from Nuclear Island called Main Complex. It is designed to withstand extreme external hazards, such as aircraft impact, extreme weather conditions, flooding due to river embankment failure, and extreme seismic events.

The building layout is 38m x 32m. Embedment is ~12m and the maximum height above the terrain is ~6.5m. It is three storeys reinforced concrete structure consisting in 2 basement level and 1 surface level. Entry gates are designed at higher level than the surface level to prevent from water intrusion during external flooding scenario. Structural resisting scheme is made of three parallel large shear walls in each direction X and Y. For external walls and roof slab, minimal thickness 1.30m offers aircraft impact protection, in accordance with EUR recommendations. In addition, entry gates are protected by independent bunkers. A platform is planned outside to connect mobile emergency generator and transformer. In addition, seismic category I water well is installed close to the building to provide backup water to the AAF and ASI systems during Design Extension Conditions event.

Owner's constraints and construction sequencing makes that prior to the erection of the building, excavation pit and diaphragm wall (DW) are realized in advance. Due to the proximity of other safety related structures, DW is seismically designed for construction period. The design earthquake loading for the pit equals to the earthquake load of the adjacent existing safety related structure The building embedded walls are poured directly against DW without any gap, after waterproofing mem-brane is intercalated. Thus, good global seismic stability of the building is demonstrated especially by crediting friction (like a stuck drawer effect). DW does not have any other permanent structural function in operation phase of the facility. However, its presence into the ground, as a stiff shell, in particular the bottom parts below the basemat level, can affect notably the SSI response by impacting waves propagation and reflection.

Design basis for nuclear licensing is according to American codes. In addition, the design shall satisfy Eurocodes and Slovenian national appendices for construction permits.

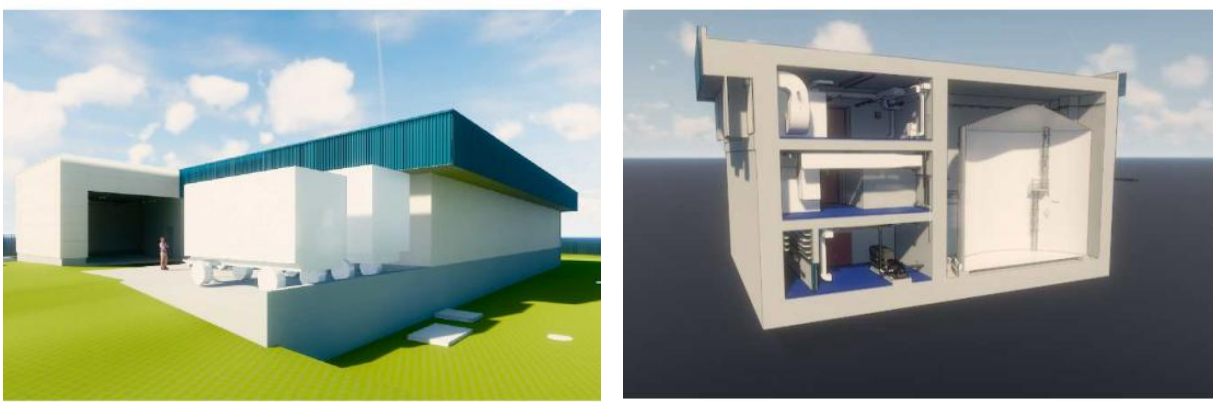


Figure 2. Krsko Bunkered Building 2 (BB2)

SEISMIC REQUIREMENTS

The different peak ground accelerations levels for the building design are (horizontally and vertically):

OBE : 0.3g | SSE: 0.3 | DEC = 2xSSE: 0.6g | DEC NEK = 1.3xDEC: 0.78g

For the DEC systems and equipment inside Nuclear Island and on the free field ground, the PGA intensity corresponding to DEC is 0.6g, which is equal to two times the design Safe Shutdown Earthquake (SSE), the latter representing the design based earthquake for systems, structures and components of NEK. The intensity was selected based on the NPP Krsko analyses of potential improvements, and the fact that thus value is higher than that as estimated for the return period 10 000 years according to the existing Krško probabilistic Seismic Hazard Analysis. For the BB2 and in-housed major DEC equipment, the design earthquake is actually chosen higher at 0.78g (0,6g x 1.3). Multiplication factor 1.3 takes approximately into account the effect of the potential uncertain-ties related to Krsko seismic hazard calculation by anticipation of possible future revaluations.

As the building is an ultimate safety building, it was specified to consider for DEC conditions the same materials design criteria than for SSE coming from the applicable design codes (no relaxation of criteria allowed). In a second step, seismic margin assessment was carried out to study beyond design robustness with respect to even higher earthquake intensity and plot fragility curves.

The shape of the design spectra is represented by the elastic response spectra defined in RG 1.60 applied at BB2 basemat level. In concertation with Slovenian actors, it was indeed justified that such standard spectrum together with PGA 0.78g assumption offers conservative conditions, in comparison with deconvolution/convolution at basemat level of the Krsko surface rock outcrop Ultimate Hazard Spectrum. 3 input ground motions are then generated matching with the design spectra RG1.60.

SOIL PROPERTIES AND SITE RESPONSE ANALYSES

Input soil profile is described in Figure 3 (left). Bedrock is assumed at 130m depth. It is basically like a bi-layer soil, made with one soft 25m thick layer on top of one medium stiffness medium. Site response analyses are conducted using SHAKE software which considers the response associated with vertical propagation of shear waves through an equivalent linear viscous system. Strain compatible soil properties are developed, for each target earthquake intensity, by convolutions analyses. For that purpose only, 6 input horizontal recorded time histories on rock are considered as a fictitious rock outcrop motion. The reason real time-histories are used, instead of the design synthetic RG1.60 time-histories, is that it is anticipated that they are more narrow-banded, and would have less tendency to overdrive the soil, and thus produces soil strains more realistically. Iterative procedure is carried out to set the ground acceleration at the desired intensity at basemat level by linear scaling of these input motions.

The effective shear modulus and soil damping strongly depend on the soil strains. Two assumptions for reduction curves are selected: (1) the Seed and Idriss (1970) curves derived for "sand"; (2) the EPRI (1993) curves derived for "soils in the general range of gravelly sands to low plasticity silty or sandy clays".

Then, for each PGA assumption, compatible soil properties are defined as the median values of all simulations (2x6). Hysteretic damping ratio is limited to 15% in accordance with USNRC regulations.
It is remarkable that, due to the particular soil profile, seismic response of the soil column exhibits a kind of bullwhip effect, amplifying motions into the upper softer layers. Consequently, calculated strains are large. Yet, it is usually considered that at strains greater than 0.5%–1%, equivalent-linear analysis results become not necessarily reliable (Kalamanos 2013). Following this practice, some runs were eliminated.

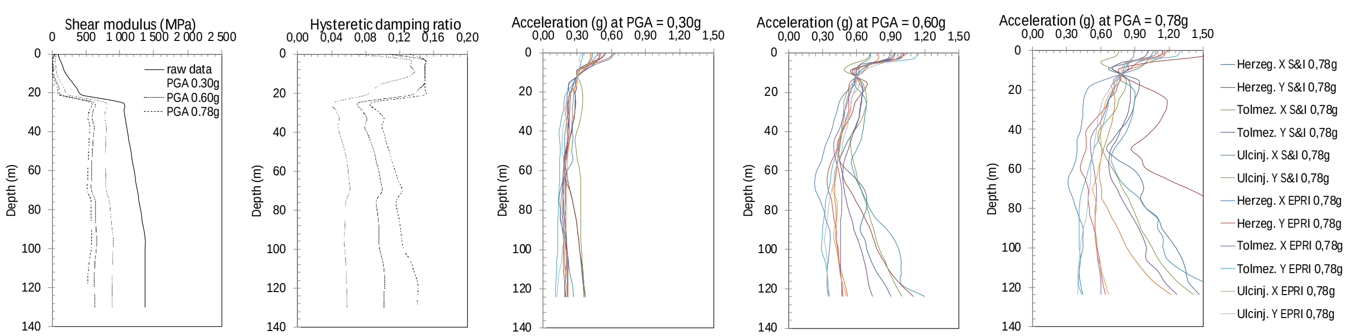


Figure 3. Computation of median compatible soil properties after site response analyses

SEISMIC MODEL AND METHODOLOGY

Modelling of soil

According to ASCE4-98, embedment effects have to be considered when depth-to-equivalent-radius is not less than 0,3. However, there is no connectivity between structure and lateral soil over the upper half of the embedment or 6m, whichever is less. The method of analysis is based on a substructuring concept that requires modelling the free-field as horizontal layers and the excavated soil occupying the embedded volume of the structure before construction. Soil outside the excavation is modelled by infinite viscoelastic horizontal layers based on the stratigraphy previously provided by SHAKE site response analysis, and half-space for sub-stratum. The layer size and node spacing respect the criteria $e < 1/5\ (v_s/f_{max})$, with f_{max} the cut-off frequency equal to 50 Hz to obtain a good transmission in a wave length. Nodes located at the interface between the soil layers and the excavated soil are interaction nodes (subtracting approach). The global SASSI model was obtained by integration of ANSYS building model into the soil-foundation model (Figure 4), by means of springs (as described by Anderson 2013).

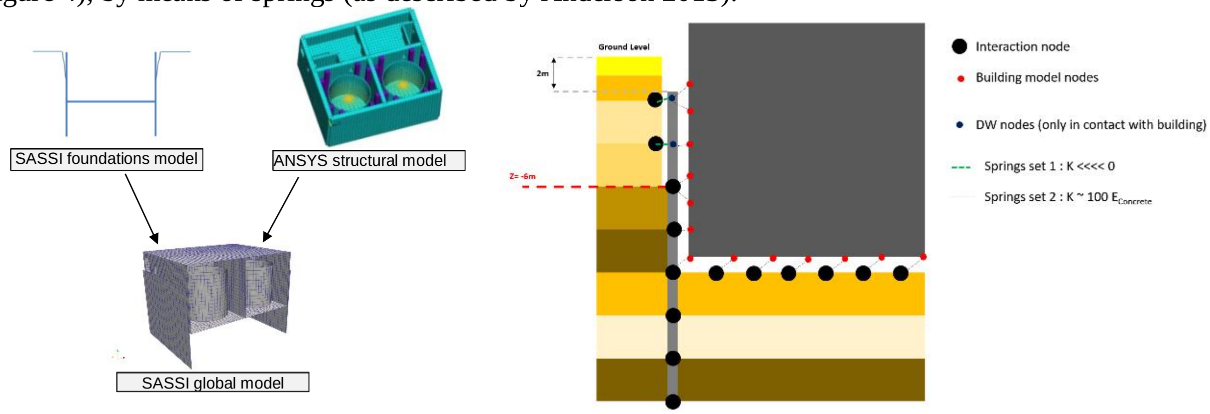


Figure 4. Principles of integration of ANSYS building model into SASSI soil foundations model

Modelling structures

The model takes into account all structural and non-structural components, the mass of equipment in their normal operating conditions and the masses percentage associated to variable loads for seismic situation. Heavy equipment like big motors and pumps are introduced by added nodal masses (motors, pumps). Structure of the tanks is modelled as a cylindrical shell. Horizontal hydrodynamics effects are simulated according to Housner 1963 theory for fluid-structure interaction under the form of convective mass and impulsive mass (see also ACI350). Walls and slabs are modelled by shell elements at their middle fibre. The total mass of the structure (without counting for the retaining wall) is 30 500 tons.

Damping ratio is 4% to 7% for concrete, 2% to 3% for water impulsive mode, 0.5% for water sloshing mode, and 2% to 3% for welded tanks structure, for PGA 0.30g to 0.60g-0.78g respectively.

Cracking is not accounted for massive low slenderness building braced with shear walls (H/L = 0.61 and E = 30000 MPa). The consensus was that the +/-15% broadening of in-structure response spectra that is usually specified for other uncertainties can also account for the variation in structural properties (see ASCE 4-98). Cracked best-estimate modulus is only applied to slabs (20000 MPa).

Dynamic analyses

Transient analyses are carried out separately for the three earthquake directions. FRS are generated at each monitoring point, for each degree of freedom of translation, in accordance with usual suggestions for frequency intervals, and combined by SRSS (see RG 1.122) To account for soil property variability, three independent calculations for each PGA are conducted using median (G), lower bound $G_{min} = G/(1+COV)$, and upper bound $G_{max} = G*(1+COV)$ (see NUREG-0800 and ASCE 4-98) The smoothed envelop is finally prepared, including +/-15% broadening of median case.

RESULTS AND DISCUSSION

Seismic response of the building is a typical rigid body motion on top of soil spring. SSI significantly modifies the modal frequencies and damping (see Figure 11).

- Period ratio is between 1.5 and 5
- Composite damping is $\tilde{\xi} = \xi_f + \frac{\xi}{(\tilde{T}/T)^3} \approx \xi_f$

Figure 5 represents the main translation modes superposed onto the design spectrum. The calculated relative displacements and absolute acceleration of the building are plotted in Figure 6. It shows the non-linear response with respect to seismic intensity, because of unpredictable SSI sensitivity. A moderator effect is remarkable regarding horizontal accelerations when seismic level rises: compatible soil properties are degraded so that modal periods moves and radiation damping increases; as a consequence, the ratio Sa/PGA is maximal at PGA 0,6g, and then decreases for higher PGA > 0,6g. On the contrary, in vertical direction, the building response remains on the peak of the design spectrum whatever the PGA and acceleration sensitivity is therefore almost linear. Concerning displacement, exponential evolution is observed in all directions.

Floor response spectra are plotted in Figure 7 under the form of dimensionless parameters Sa/PGA. They represent the smoothed envelop values computed for soil variability G_{min}, G_{med} (broadened +/-15%) and G_{max} for each PGA assumption. Maximal values per slab level are selected among various monitoring points in the structure. Results can be interpreted as follows:

- In horizontal direction:

ü main peaks are logically observed at the fundamental SSI modal frequency in translation. Frequency variations with PGA is consistent with the soil stiffness decrease. Amplitude variations of the peaks and the ZPA is directly impacted by the moderator effect discussed above.

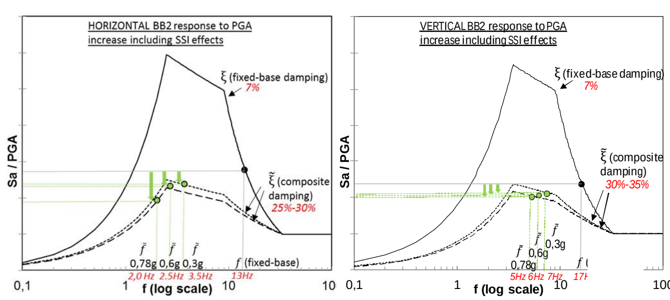
ü small peaks correspond to secondary modes. Frequency does not match with the fixed-base modal frequencies of the building, so that it is again an SSI mode as the building is very rigid. It is remarkable that at 0,30g there is a clear difference be-tween the roof corner response and the basemat center (= rocking mode), whereas at 0,78g the response is similar whatever the point in the building (= apparition of second translation mode instead of rocking, when compatible soil is so flexible that it cannot stiffen DW foundation legs, as illustrated in Figure 8). It demonstrates the nature of secondary modes and damping can change notably when increasing the seismic intensity, which is another moderator effect.

- In vertical direction:

ü main peaks are naturally observed at the building modal frequency in vertical translation. Frequency variations with PGA are consistent with the compatible soil stiff-ness decrease. Peaks and ZPA amplitudes are stable in the absence of moderator effect vertically, as discussed above.

ü the rocking motion at 0.30g is visible on the ZPA difference between basemat and roof level.

ü the second large peak at 17 Hz is explained by local vibration of the roofslab. The peak frequency is independent from the PGA assumption, and resonance amplitude varies.



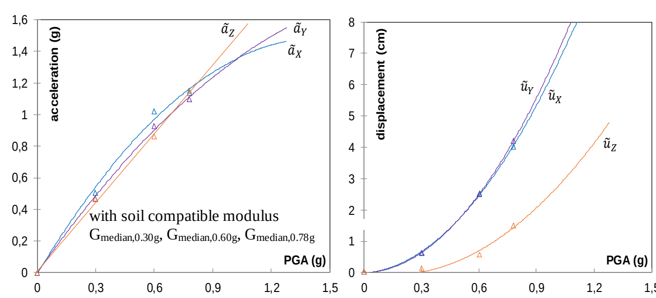


Figure 5 (left). RG1.60 design spectrum and illustration of moderator effect related to main translation modes
Figure 6 (right). Relative displacements and absolute acceleration at buried pipes connection point

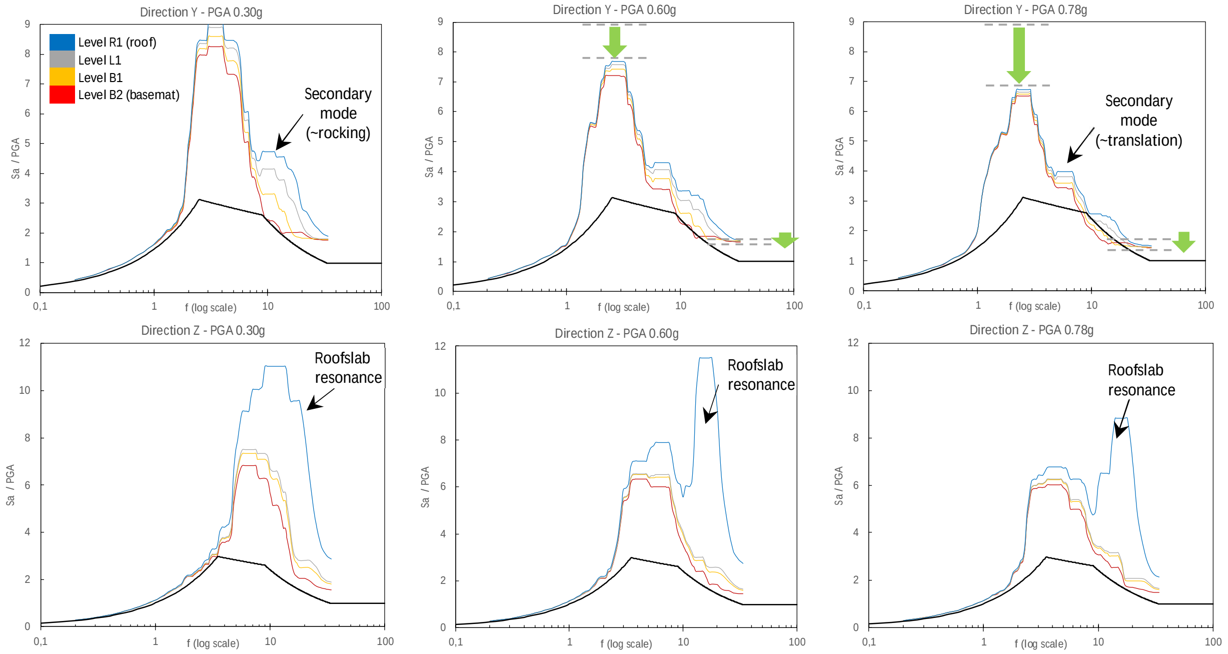


Figure 7. Envelop floor response spectra (5% damp.) for different earthquake levels and soil variabilities

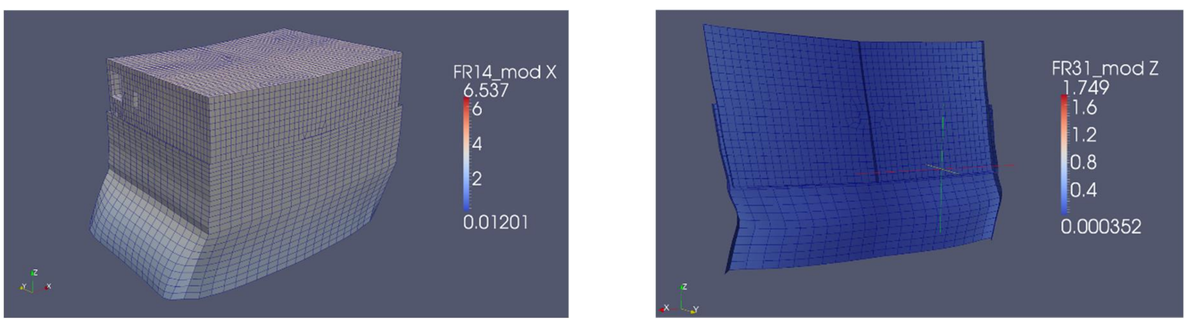


Figure 8. Paraview plotting of the SASSI model and transfer function nodal values calculated at the main (left) and secondary (right) modes frequencies (horizontal excitation, soil $_{\text{Gmedian, 0.78g}}$).

COMPOSITE DAMPING ESTIMATE

In order to quantify composite damping, Ostadan (2004) proposed an energy dissipation measurement methodology either through free vibration of forced vibration steady state tests. Here, another methodology is developed: as it was demonstrated that BB2 seismic response is quite similar to rigid body motion above soft soil, a simplified model was prepared consisting in one single 6D oscillator. Frequency dependent impedances properties of stiffness and damping were previously evaluated by means of a second SASSI model of the construction pit only and submitted to harmonic analyses (substructure impedance method). After calibration at the relevant modal frequencies, final adjustments were iteratively made in each of the degrees of freedom so that FRS match with the direct solution technique results at basemat center and roof corners. Torsion is not studied because it is very stiff in all case and not impacting. Validity of such simplified model shall be limited in certain conditions to verification purpose of the complete SASSI model, or to sensitivity analyses such as accidental torsional eccentricity. It may not capture well the complex SSI higher modes nor the dynamic soil pressure effects on global reaction. Figure 9 presents the comparison after calibration of damping, or for limited damping at 20% according to NUREG guidance.

- Case PGA 0,30g with soil Gmax,0.30g :
  - ü FRS can be reproduced accurately by means of simple oscillator. Composite damping is set 20%, 20%, 25% for horizontal translation, vertical translation and rocking respectively.
  - ü When damping is limited to 20%, only minor increase is observed, but remaining acceptable for design of systems.
- Case PGA 0,78g with soil Gmin,0.78g :
  - ü Composite damping is set 27% and 28% for fundamental horizontal and vertical translation respectively. Calibration of frequencies and damping is less accurate be-cause eigen frequencies are in the zone of sudden change in the RG1.60 design spectrum (junction of flat plateau and descending branch). Disappear of rocking motion is obtained by introducing very high damping ratio (>100%). Although maybe physically surprising, it is actually consistent with application of usual analytical formulations for impedance when very soft soil conditions are considered. Such high damping values were already remarked in past papers (Hadjian 1995). Moreover, the second peak coming from secondary horizontal translation mode cannot be reproduced by the single oscillator.
  - ü When damping is artificially limited to 20%, significant increase of accelerations is obviously observed. It proves that in very soft compatible soil conditions, direct solution technique offers great benefits compared to impedance method, capturing all SSI modal contributions and real radiative damping. Design of building structure and components inside is therefore optimized.

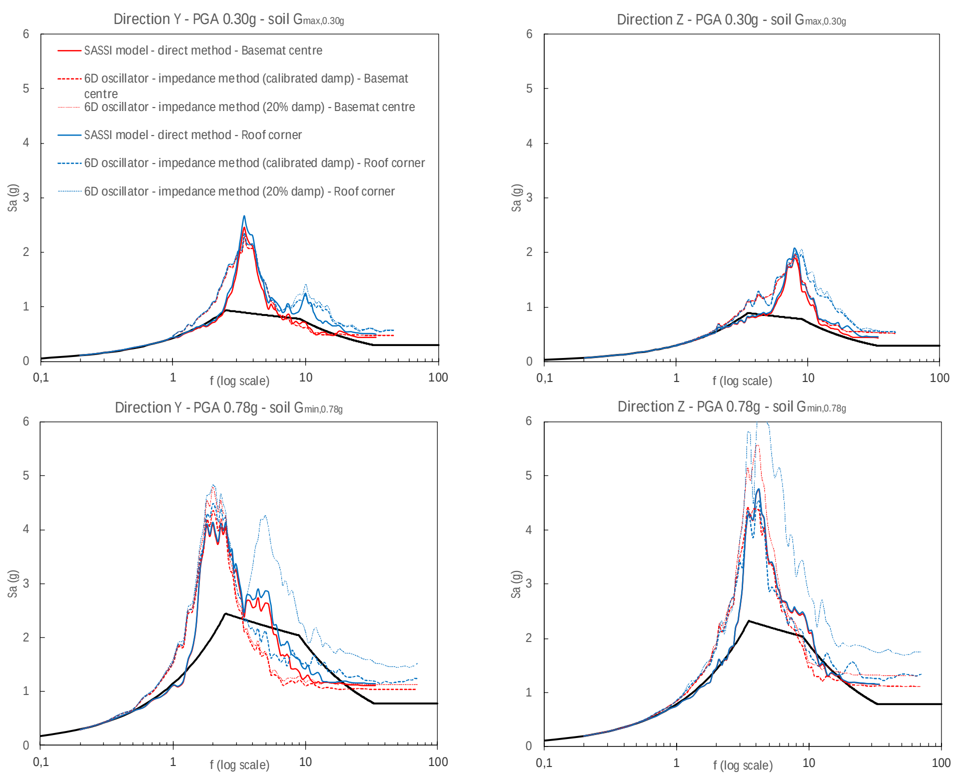


Figure 9. FRS comparison: impedance method vs. SASSI direct solution method

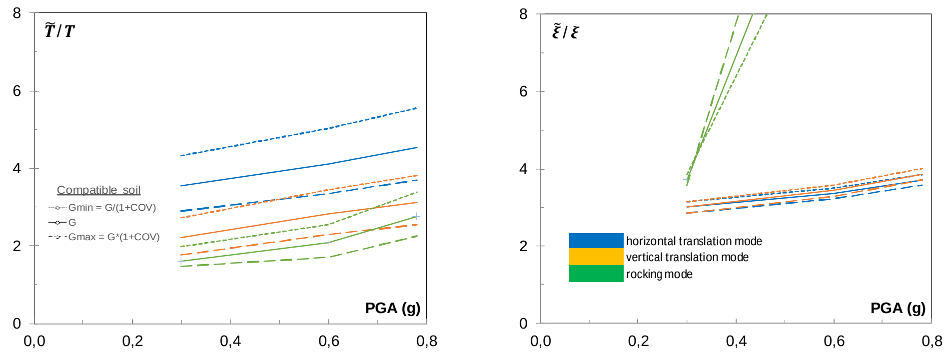


Figure 10. Main period and damp. ratios compared to fixed-base building for different seismic intensities

ILLUSTRATION OF COMPLEX KINEMATIC EFFECTS

Sensitivity analysis was carried out to assess the impact of the DW construction pit on the soil-structure-interaction response. 3 calculations were compared with the help of the SASSI model by direct method: (1) DW is connected to the building (= reference case called H); (2) DW bottom legs are removed from the model (case called U); (3) a joint between DW and building lateral walls is assumed (case called |-|). At 0.78g, it is observed on FRS :

- Insignificant difference between H and |-| models.
- The presence of DW bottom legs in the ground have great effect compared to U model.
  - ü Horizontally, the main peak frequency is moved, confirming that DW legs change the soil stiffness. As a result, peak and ZPA amplitudes are modified because the frequency is in the ascending branch area of design spectra. Secondary peak amplitude is also modified.
  - ü Vertically, the peak frequency is not modified making think that soil stiffness is not sensitive to DW, but the peak amplitude and the zero-period acceleration are much reduced. As a rigid shell embedded in the soft surrounding ground, the DW legs be-low the bottom of construction pit notably affects the wave propagation and reflection in that region. Amplitude variations actually highlight soil radiative damping modification.

This example demonstrates the importance to consider the DW in the model, in order to capture adequately the correct stiffness and complex seismic wave field below the basemat, especially into a soft soil. In such configuration, the use of a detailed soil-structure interaction model appears mandatory, whereas the validity of usual analytical impedance formulations remains limited.

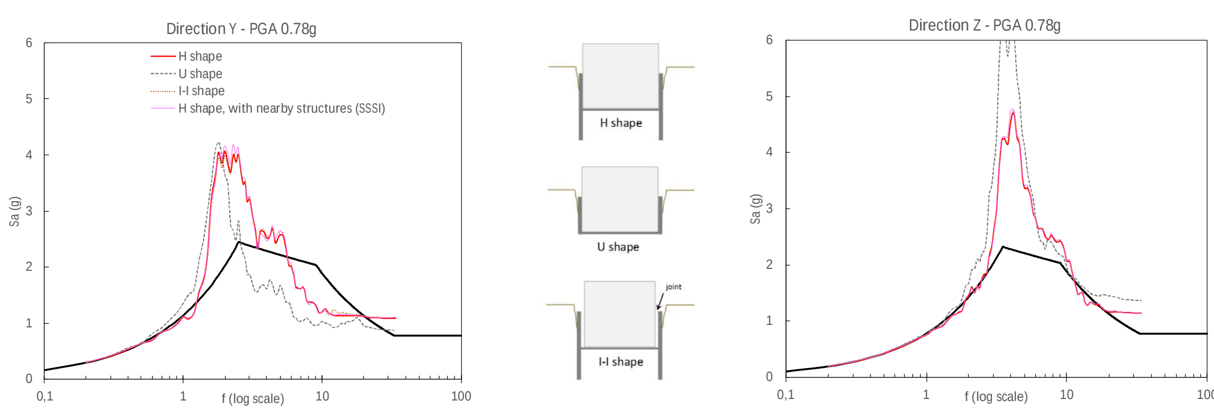


Figure 11. FRS sensitivity to construction pit shape (basemat level, no smoothing, no broadening, soil $G_{med,0.78g}$) and to structure-soil-structure interaction

STRUCTURE-SOIL-STRUCTURE INTERACTION (SSSI)

Sensitivity analysis was carried out to assess the impact of other civil structures in the vicinity of the building. A new model was prepared to include in a simplified way the presence of a smaller building (mass 13 ktons ; footprint 26m x 22m) at surface level and 10m distance, and also the Sava River cut-off wall (depth 14m) at distance 15.5m (Figure 12). Comparative analyses revealed minor differences with or without structure-soil-structure interaction (Figure 11). The maximal deviations on FRS is observed mostly around frequency 1.8 Hz. It is remarkable in this case that such frequency corresponds approximately to a surface wave length (λ = v/f) equal to 4 times the total length of all adjacent buildings. This may be interpreted as a situation of possible interaction (see IAEA TecDoc). However, the SSSI effects remain actually limited to 2%-6% variation compared to SSI in our example. Our results are consistent with expected behavior: the influence of nearby structures is usually disregarded unless significant heavier building is close (ASN French guidelines or American study 2015) thus offering computing time savings.

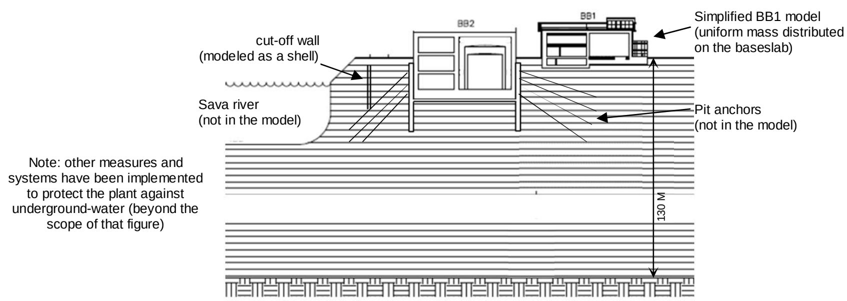


Figure 12. Nearby structures considered for structure-soil-structure interaction sensitivity study

CONCLUSION

SSI effects have great incidence on the seismic response in soft soil conditions. It significantly modifies the fundamental modes deformed shape, frequencies and damping. Frequency usually moves in the range of the design spectrum plateau. In the meantime, damping ratio is driven by the soil. All things considered, at design earthquake level (DBE), the building can be submitted to relatively homogeneous acceleration field, and lower demand than in fixed-base conditions.

For higher earthquake level (DEC), when site response analysis is previously revised to establish the compatible soil properties, the increase of accelerations in the building is not proportional to PGA: moderator effects comes from possible shift of horizontal fundamental frequencies outside the peak zone of the design spectrum, together with larger damping ratio.

In even higher earthquake conditions (beyond design), that statement could be considered to exhibit hidden margins, when carrying out probabilistic fragility analysis, also named seismic margin assessment (SMA), for the building structures and components inside. On the contrary, as displacement increase is non-linear, possibly exponential, special attention shall be paid to fragility analysis of buried pipes connections to demonstrate robustness of design and absence of cliff-edge effects coming from sudden failure.

The example discussed in this paper highlights the benefits of direct solution method, in comparison with impedance method. The latter suffers in certain soft soil conditions from artificial limitation of damping by regulations (<20% in US licensing basis) and does not reflect secondary modes effects. Results remain similar for design conditions at PGA 0.30g, but impedance method appears conservative for higher earthquake levels, thus leading to potential technical and financial risks for the project.

Seismic response of the embedded building is sensitive to how the construction pit is modelled, whose bottom foundation legs significantly affect horizontal stiffness and vertical damping. No analytical formulation gives reliable impedances nor damping in such conditions. The use of advanced numerical code, such as SASSI, sounds mandatory to capture the complex wave field under H shaped diaphragm wall.

Structure-soil-structure interaction (SSSI) can be disregarded when nearby buildings are lighter.

AKNOWLEDGEMENT

Nuklearna Elektrarna Krško (NEK) and Ansaldo Nucleare (ANN) are acknowledged for supporting this paper. Discussions with Faculty of civil and geodetic engineering (University of Ljubljana) throughout the design process of the BB2 building are also gratefully emphasized.

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